

# Nonlinear Degree-Day Models for Postdiapause Development of the Sunflower Stem Weevil (Coleoptera: Curculionidae)

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**ABSTRACT** The sunflower stem weevil, *Cylindrocopturus adspersus* (LeConte) (Coleoptera: Curculionidae), has caused yield losses across much of the western Great Plains. Little is known about the field biology of this pest. Simple prediction models, such as degree-day models, are an integral tool for development of *C. adspersus* management strategies. Using data collected in Colorado, Kansas, and Nebraska, we sought for predictable variation between *C. adspersus* pupation, adult eclosion, and emergence and accumulated degree-days Celsius (DD) by using a temperature threshold of 5°C. Accurate phenological models can be used to time scouting efforts and pesticide applications. The relationship between phenological data and accumulated DD fit nonlinear, Gaussian distributions better than uniform distributions. Phenological models were developed to describe these distributions for pupation, adult presence within the stalk and adult emergence. The pupation model predicts 50% pupation at 197 DD and 90% at 307 DD. Model results predict that 50% of adult eclosion within the stalks will have transpired at 396 DD and 90% at 529 DD. A model-averaged result from two data sets predicts 5% adult emergence from stalks at 262 DD, 50% emergence at 540 DD, 75% emergence at 657 DD, and 90% at 777 DD. Scouting for adults thus can be initiated at 262 DD. Current chemical controls target adults to prevent oviposition. Thus, applications therefore should not be made before this point.

**KEY WORDS** *Cylindrocopturus adspersus*, degree-day model, predictive model, sunflower stem weevil

One of the most important row crops in North America is the cultivated sunflower, *Helianthus annuus* L. Bangsund and Leistriz (1995) estimated that the economic impact of the United States sunflower industry was >\$2.5 billion annually. In 2008, ≈2.5 million acres was planted to sunflower (USDA–NASS 2009), and the price of sunflower seed has increased by >10% annually since 2002 (USDA–NASS 2009). These indicators demonstrate the growing value of this crop and the growing need to protect this crop from pest damage. Numerous sunflower pests exist, many of which can dramatically reduce yields (Charlet 1999). One of the most damaging of these pests is the sunflower stem weevil, *Cylindrocopturus adspersus* (LeConte) (Coleoptera: Curculionidae), which has caused significant yield losses in sunflower producing states west of the Mississippi River (Rogers and Jones 1979, Armstrong 1996). Larval feeding within stem vascular tissues can reduce sunflower yields and often causes plant lodging (Rogers and Jones 1979). Preharvest lodging has resulted in 80% yield loss (Armstrong and Koch 1997, Knodel and Charlet 2002). Females deposit eggs under the epidermis in the basal region of the sunflower

stalk. After hatch, the larvae feed on pith and conductive tissue (Rogers and Jones 1979, Knodel and Charlet 2002). Mature *C. adspersus* larvae overwinter in the sunflower stalk below the first node above the ground and within the root crown below ground level (Rogers and Serda 1982, Charlet 1983a). Larvae continue their development within the stalk, pupate and eventually emerge as adults in late spring and early summer of the following year (Rogers and Serda 1982). After emergence, adults feed on sunflower plants, mate, and oviposit. In addition to feeding damage, *C. adspersus* also is associated with the stalk rot diseases Phoma black stem (*Phoma macdonaldii* Boerma), which contributes to premature ripening syndrome, and charcoal stem rot [*Macrophomina phaseolina* (Tassi)] (Gaudet and Schulz 1981, Yang et al. 1983).

Management tactics for *C. adspersus* include delayed planting (Rogers and Jones 1979, Oseto et al. 1982, Rogers et al. 1983), stalk burial (Charlet 1994), and the use of insecticides (Rogers and Jones 1979, Charlet and Oseto 1983, Rogers et al. 1983, Charlet et al. 1985). Natural enemies, including numerous species of Hymenoptera, have been found reducing *C. adspersus* populations (Rogers and Serda 1982, Charlet 1983b, Charlet et al. 2002). However, efficient biological controls for *C. adspersus* do not currently exist (Charlet 1983b, Charlet et al. 2002). Compared with cultivated sunflower, some native sunflower species

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have shown significantly less foliar feeding and significantly fewer larvae (Rogers and Seiler 1985, Barker 1990). Their findings have implications for the development of resistant sunflower cultivars. Monitoring for *C. adspersus* is made difficult by its size, coloration and behavior (Knodel and Charlet 2002). Current monitoring recommendations call for scouting from late June through mid-July, which is logistically difficult and costly. An increased knowledge of the phenology of *C. adspersus* is needed to improve current integrated pest management (IPM) practices (Charlet 1987). Prediction models for the emergence of *C. adspersus* could improve timing of scouting efforts and of insecticide treatments. Predictive models exist for predicting emergence of adults from the stalk but were developed from data obtained over a limited time period or from a limited geographical range. Charlet (1987) examined *C. adspersus* in North Dakota and found that initial emergence of adults from stalks occurred at 420 degree-days Celsius (DD) and that 90% of emergence had occurred by 865 DD (using a temperature threshold of 5°C). In Colorado, Armstrong (1996) observed first emergence at 379 DD and found 90% emergence had occurred at 651 DD (using a temperature threshold of 5°C). To our knowledge, no DD models exist for determining timing of pupation and adult eclosion within the stalk. Our goal was the development of a DD prediction model for *C. adspersus* pupation, adult eclosion within the stalks, and adult emergence from the stalk.

### Materials and Methods

**Pupation and Appearance of Adults Within Stalks.** Data were collected in 2003 and 2004 in Washington (eastern Colorado), Phillips (northeastern Colorado) and Yuma (northeastern Colorado) counties in Colorado and Sherman county (northwestern Kansas) in Kansas. Previous-year sunflower stalks were collected weekly starting 30 March of each year. Every week, 30 stalks with their crowns and roots were removed from each of the four field sites. In total, 1,560 stalks were collected over 13 wk in 2003, and 1,440 stalks were collected over 12 wk in 2004. Stalks were dissected and the developmental stages of *C. adspersus* determined. Each *C. adspersus* developmental stage (larva, pupa, and adult) was recorded during dissection of the stalks. Sampling continued until no *C. adspersus* were observed in the samples.

Daily maximum and minimum temperatures were obtained for these sites from the nearest Colorado State University weather stations. DD were tallied from 1 January of each year by using a temperature threshold of 5°C (Charlet 1987, Armstrong 1996, Armstrong and Koch 1997). Specifically, DD were calculated in Celsius as follows:

$$DD = (\text{maximum temperature} + \text{minimum temperature}) / 2 - 5^{\circ}\text{C}$$

For each sampling date, accumulated DD were calculated by summing DD from 1 January through the

current sampling date. If weather stations failed to collect temperature data, data were collected from the next closest Colorado State University weather station provided temperature readings. Therefore, weather stations ranged from within meters to >10 km away. Distance from site to weather station could result in substantial noise in the data. However, temperature data for this region are relatively stable.

We hypothesized that the relationship between DD and phenological stages were either 1) linear, with uniform counts detected for a period during in each phenological stage; or 2) nonlinear, with an approximately bell-shaped curve (i.e., counts increasing with increased DD to a peak and then decreasing as the season progressed). Counts were transformed into cumulative fractions of yearly counts. Data were analyzed as a function relating the cumulative fraction of yearly counts to accumulated DD. The cumulative fraction of each developmental stage of *C. adspersus* was fit to the accumulated DD data using regression models (Proc Reg, SAS 2002–2003) or logistic models (Proc Nlin, SAS 2002–2003). The linear model form was as follows:

Cumulative fraction of *C. adspersus*

$$\text{developmental stage} = \alpha * DD + \beta$$

where  $\alpha$  and  $\beta$  are the slope and intercept, respectively. The nonlinear function was as follows:

Cumulative fraction of *C. adspersus*

$$\text{developmental stage} = 1 / (1 + \alpha * e^{(\beta * -DD)})$$

where  $\alpha$  and  $\beta$  are modifiers to the logistic (sigmoid) function. Akaike's Information Criterion (AIC) (Akaike 1981, Burnham and Anderson 2002) was used to select the appropriate model (i.e., either linear or nonlinear) for each developmental stage. The model with the lowest AIC was then used to describe the relationship between accumulated DD and each stage.

**Adult Emergence From the Stalk.** Methods for determining *C. adspersus* emergence from stalks differed primarily because additional data set were available for examining emergence. The first emergence data set was developed as described above. To obtain *C. adspersus* emergence numbers, we calculated the decline in the number of adult weevils within the stalk from 1 wk to the next. The decline in number of adults present in the stalk was used as an indicator of *C. adspersus* emergence from stalks. Thus, percentage decline in the number of adults was considered as percentage emergence. Cumulative percentage of adult emergence from stalks was determined for each sampling date. These data were used to develop *C. adspersus* Emergence model 1.

Additional emergence data were collected in 1996 and 1997 at Thomas County, KS (northwestern Kansas) (1996 only); Cheyenne County, KS (northwestern Kansas); Scotts Bluff County, NE (western Nebraska); Ellis County, KS (central Kansas); and Washington County, CO (eastern Colorado). Each year at each site, six sets of 10 previous-crop sunflower

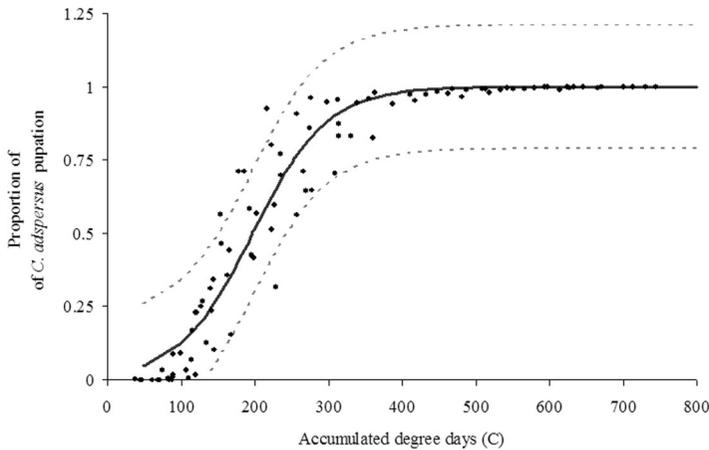


Fig. 1. *C. adspersus* pupation. Logistic model of cumulative *C. adspersus* pupation as a function of accumulated DD (solid line) with 95% CL (dashed lines). Black circles are observed data.

stalks were collected in early April and placed under screen cages in the field. Cages were monitored every 2 to 3 d from mid-May through July for adult *C. adspersus*. All adults were removed from each cage on each sample date. The maximum and minimum temperatures were collected from the nearest National Weather Service Station then used to calculate DD and to develop *C. adspersus* emergence model 2.

**Model Fitting.** *C. adspersus* emergence was assumed to be either linear (uniformly distributed emergence) or nonlinear (Gaussian-distributed emergence). Data were analyzed as the cumulative fraction of the total collected correlated to the number of accumulated DD. Similar to the modeling techniques used for the pupal and adult eclosion stages, functions were fit to *C. adspersus* emergence data using Proc Reg (SAS 2002–2003) and Proc Nlin (SAS 2002–2003). The forms of the linear and nonlinear functions were as described above.

Because data collection methods differed, emergence model 1 and emergence model 2, were developed separately. That is, the lowest AIC values were used to select either a linear or nonlinear model for each data set independently (Akaike 1981, Burnham and Anderson 2002). Models selected from each data set were then weighted based on the inverse of the mean squared error (MSE) between observed data and model predictions. Weights were standardized to sum to 1. The two resulting weighted emergence models were then combined using a weighted average:

$$\begin{aligned} \text{Combined emergence model} \\ = \text{EM1} * w_{\text{EM1}} + \text{EM2} * w_{\text{EM2}} \end{aligned}$$

where EM1 and EM2 are equal to emergence models 1 and 2, respectively.  $w_{\text{EM1}}$  and  $w_{\text{EM2}}$  are equal to the weights for emergence models 1 and 2, respectively.

## Results

Winter severity likely affects overwintering success and timing of *C. adspersus* phenology (Charlet 1989).

To quantify winter severity, we averaged temperatures during the first 90 Julian days of each year. The coldest average temperatures were recorded in 1996 with an average of  $-0.83^{\circ}\text{C}$ , with the lowest site average  $-2.13^{\circ}\text{C}$  in Scotts Bluff County, NE. The warmest average temperatures were recorded during 2004 with an average temperature of  $1.51^{\circ}\text{C}$  across all sites and the warmest site average  $1.96^{\circ}\text{C}$  in Sherman County, KS.

The earliest observations of *C. adspersus* pupae were on the 19 March 2004 sampling date at the Sherman County, KS, and Phillips County, CO, sites. The first adult occurrence within the stalk was on the 16 April 2004 sampling date in Washington County, CO. The first adult weevil emerged on 2 May 1997 at the Washington County, CO, site at 410 DD.

The nonlinear, logistic model fit the data better than the linear model for all phenological stages (pupation: linear AIC =  $-296.6$ , nonlinear AIC =  $-415.0$ ; adult: linear AIC =  $-221.7$ , nonlinear AIC =  $-256.7$ ; emergence model 1, linear AIC =  $-27.3$ , nonlinear AIC =  $-31.0$ ; and emergence model 2: linear AIC =  $-1163.0$ , nonlinear AIC =  $-1199.7$ ). Because the nonlinear model AIC values were lower (i.e., better) in all cases, the nonlinear, logistic models were used to analyze results.

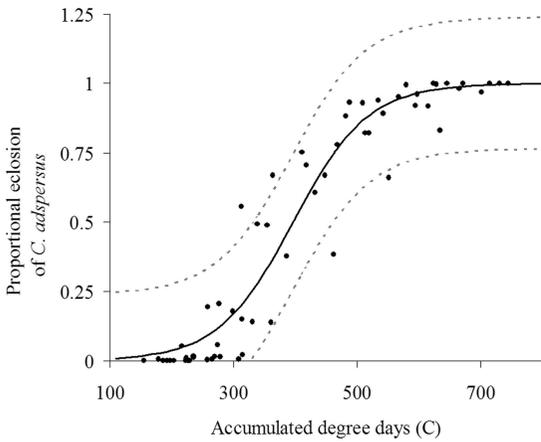
**Pupation and Adult Eclosion.** The pupation of *C. adspersus* was suitably described using a fitted logistic model (F-stat = 2150.42; df = 2, 93;  $P < 0.0001$ ):

$$\begin{aligned} \text{Cumulative fraction (pupation)} \\ = 1 / (1 + 49.6 * e^{(-\text{DD} * 0.0199)}) \end{aligned}$$

The model predicts 5% pupation at 48 DD, 50% pupation at 197 DD, 75% pupation at 252 DD, and 90% at 307 DD (Fig. 1).

Adult *C. adspersus* eclosion was suitably described using a fitted logistic model (F-stat = 873.02; df = 2, 59;  $P < 0.0001$ ):

$$\begin{aligned} \text{Cumulative fraction (adult)} \\ = 1 / (1 + 701.2 * e^{(-\text{DD} * 0.0165)}) \end{aligned}$$



**Fig. 2.** *C. adspersus* eclosion. Logistic model of cumulative emergence of *C. adspersus* adults from pupae as a function of accumulated DD (solid line) with 95% CL (dashed lines). Black circles are observed data.

The model predicts 5% adult eclosion at 218 DD, 50% at 396 DD, 75% at 463 DD, and 90% at 529 DD (Fig. 2).

**Adult Emergence From Stalks.** Adult emergence from stalks was modeled using fitted logistic models. Emergence model 1 (F-stat = 207.42; df = 2, 20;  $P < 0.0001$ ) was suitably described by the logistic formula:

Emergence model 1: cumulative fraction

$$= 1 / (1 + 459.4 * e^{(-DD * 0.0125)})$$

Emergence model 1 predicts 5% adult eclosion at 255 DD, 50% at 490 DD, 75% at 578 DD, and 90% at 666 DD (Fig. 3).

Emergence model 2 (F-stat = 2557.59; df = 2, 331;  $P < 0.0001$ ) was suitably described by the logistic formula:

Emergence model 2: cumulative fraction

$$= 1 / (1 + 226.1 * e^{(-DD * 0.0091)})$$

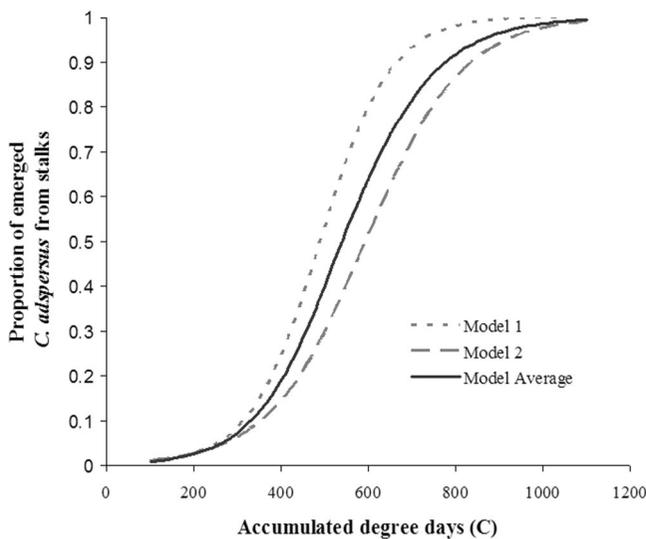
Emergence model 2 predicts 5% adult eclosion at 272 DD, 50% at 594 DD, 75% at 715 DD, and 90% at 835 DD (Fig. 3).

Both models had similar MSE and therefore similar weights (emergence model 1's weight was 0.56 and emergence model 2's weight was 0.44). Using these weights, models were averaged. Combined model results were as follows: 5% emergence occurred after 262 DD, 50% after 540 DD, 75% after 657 DD, and 90% emergence occurred after 777 DD.

**Discussion and Conclusions**

Understanding *C. adspersus* phenology in relation to weather will enhance IPM practices by enabling more efficient scouting and better timed insecticide applications. In addition, adult emergence prediction models will help us better understand the consequences of altering sunflower planting dates. Prediction of other life stages of this pest may allow us to target potentially vulnerable life stages with control tactics.

It is a concern that emergence models 1 and 2 estimated different peak emergence. Differences in methodology in data collection may explain some of the differences in values obtained between these models. That is, Rogers and Serda (1982) reported that *C. adspersus* adults chewed exit holes but then might remain in the stalk for several days or weeks until emergence was prompted by a significant rainfall event. Differences may be due to differences in data



**Fig. 3.** *C. adspersus* emergence. Logistic models of cumulative emergence of *C. adspersus* adults from sunflower stalks as a function of accumulated DD depicting two models from different data sets (dashed lines) and the model-averaged values (solid line). Black circles are observed data.

development methods. Specifically, data for emergence model 1 were obtained by removing stalks from the field and dissecting them, whereas emergence model 2 data were established by collection of emerged beetles (i.e., adults with exit holes cut but remaining within stalks were not considered emerged.) Disturbance caused by removal of the stalk (emergence model 1) from the field may have caused earlier emergence than would have been observed otherwise. Therefore, emergence model 1 data may be slightly conservative.

Charlet (1987) estimated 90% emergence at 865 DD. Armstrong (1996) estimated 90% emergence at 651 DD. A simple average of results from Charlet (1987) and Armstrong (1996) suggests that 90% emergence will occur when  $\approx 758$  DD have accumulated, which compares with the model-averaged result from this study of 777 DD. Data within our models, as well as the work of Charlet (1987) and Armstrong (1996) deal with populations from different locations (i.e., they may be distinct populations), which likely caused additional noise in the data. However, the relative concurrence of these figures increases confidence in our findings.

Also, accurate emergence prediction models would have significant value in areas where it is possible to manipulate planting date (Rogers and Serda 1982). That is, timing the planting of the sunflower crop so that plants are too small to be attractive for oviposition when adults are active. In addition, in areas where manipulation of planting times was not a viable alternative, predictions could be used to time scouting and insecticide applications.

Scouting for *C. adspersus* should be initiated after 262 DD have accumulated so that current chemical controls can target *C. adspersus* in the narrow window between emergence of adults from stalks and before oviposition.

Future work should concentrate on development of an increased understanding of the ecological factors impacting the timing of *C. adspersus* oviposition. More precise understanding of the factors influencing oviposition timing will allow for improved timing of pesticide applications. In addition, research toward the development of more effective biological control, host plant resistance and improved planting techniques could be highly beneficial toward controlling this damaging pest species.

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